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(71) Applicant (*for all designated States except US*): **OSMO-TEX AS** [NO/NO]; P.O. Box 6146 Postterminalen, N-5892 Bergen (NO).

(72) Inventors; and
(75) Inventors/Applicants (*for US only*): **EIDSNES, Trond** [NO/NO]; Grønnestølveien 72, N-5073 Bergen (NO). **ELLINGSEN, Olav** [NO/NO]; Kleiva 20, N-6900 Florø (NO). **HELDAL, Trond** [NO/NO]; Fantoftveien 30, Ieil 0703, N-5072 Bergen (NO). **MISHCHUK, Natalyia** [UA/UA]; Kiev 03124 (UA).

(74) Agent: **ACTIO LASSEN AS**; P.O. Box 1880 Nordnes, N-5817 Bergen (NO).

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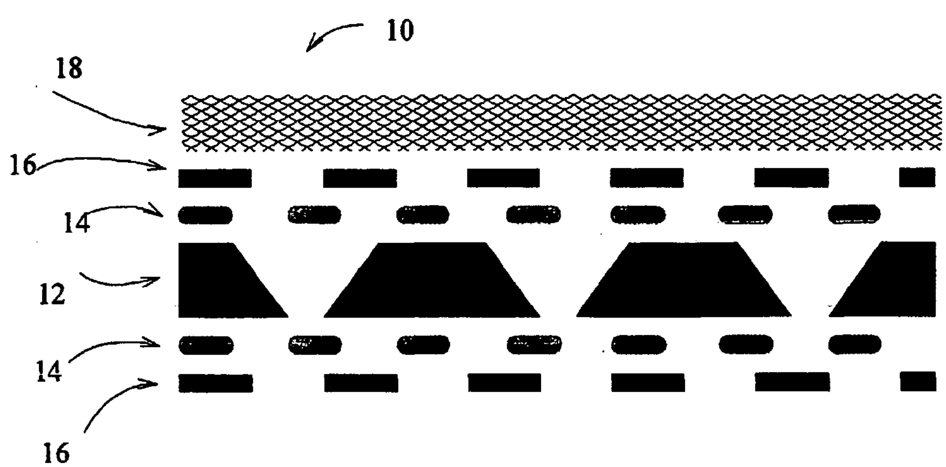
(54) **Title:** FABRIC MATERIAL WITH IMPROVED LIQUID TRANSPORT



(57) **Abstract:** The present invention describes a fabric material. The material possesses improved liquids transport across said material. The invention also relates to several applications of the fabric material.

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FABRIC MATERIAL WITH IMPROVED LIQUID TRANSPORT

FIELD OF INVENTION

The present invention relates to a fabric material. The material possesses improved liquids transport across said material. The invention also relates to several applications of the fabric material.

BACKGROUND OF THE INVENTION

In general, humidity control represents a potential problem for all things subject to water in the form of condensation, rain, perspiration, process water, ground water or other water. E.g. is the damage to buildings in most countries caused by too much water or humidity amounting to several billion USD a year.

In many cases, the best solution to the problem is at present through the uses of water barriers, e.g. non breathable polymer coated textiles. However, as this does not allow e.g. condensation water to escape from inside a building, much efforts have been put into developing materials capable of transporting liquid or humidity in the desired direction, while blocking for transport in the other direction. As several impressing results have been achieved in this field, the need for a more efficient transport system is still seen to be urgent for many applications.

The need for a material which efficiently moves liquid from one side of the material to the other, is not least desirable in clothes made for sporting and physical activities.

During physical activity, the evaporation of vapor from the skin is essential for the human body heat management, and thus for the maintenance of the body temperature. As all kind of protective garments available today represents a barrier for water and vapor transport, the body heat management is often disrupted. The clothing should ideally protect the human body from weather conditions (cold, wet, wind), from heat, or

chemically or biologically dangerous environment, while perspiration should be allowed to leave the body. From the publication J. Coated Fabrics, 1985, 15 (89) the following representative are shown:

Table 1

Heat energy and perspiration rates

Activity	**Work rate [W]**	**Perspiration rate [l / h]**
Gentle Walking	200	0.32
Active Walking with Light Pack	400	0.63
Active Walking with Heavy Pack	500	0.79
Mountain Walking with Heavy Pack	600-800	0.95 – 1.3
Maximum Work Rate	1000 – 1200	1.6 – 1.9

For shorter time periods, much larger perspiration rates have been reported.

At present, perspiration are allowed to escape through protective clothing by diffusion (through semipermeable membranes) and also by advection for the more open structures (like densely woven fabrics). Only fabrics including semipermeable membranes are both water proof and breathing. However, the diffusion mechanism is slow, thus the breathability can by no means match the perspiration rates under vigorous physical activity (table 2).

Table 2

Material	WVT (l / m²h)	
	Dry	Rain
Microporous PU coated fabric A	0,142	0.034
Microporous PU coated fabric B	0.206	0.072
2x layer PTFE laminate	0.205	0.269
3x layer PTFE laminate	0.174	0.141
Hydrophilic PU laminate	0.119	0.023
Microporous AC coated fabric	0.143	0.017
Microfibre fabric	0.190	0.050
PU coated fabric	0.018	0.004

Water – vapor transport (WVT) throught rainwear fabrics (P. Saltz, "testing the quality of breathable fabrics", Performance of Protective Clothing: Second Symposium ASTM Special Publication 1989, eds F.Z. Mansdorf, R. Sagar and A.P: Nielson, American Society for Testing and Materials, Philadelphia, 1988, p295)

Furthermore, the driving forces of fluid transport in present fabrics are the temperature, humidity and pressure differences across the membrane. Thus, in warm, wet weather conditions, this driving force may be absent, or even reversed.

In conclusion, only very limited water transport or breathability is obtained for protective clothing at present. While such fabrics can provide comfort for gentle walking in cool rainy weather, it can by no means accommodate for the larger perspiration rates at higher physical activity. In such cases, sufficient cooling is not obtained, as perspiration water is not allowed to escape. This again leads to increased perspiration rates, but with no further cooling as a result. Also, the resulting accumulation of liquid water in the inner garment

leads to the danger of cooling after the period of high physical activity, as wet heat conduction through clothing is many times faster than dry conduction. Thus, the body performance during work or sports is significantly reduced by wearing protective garments. In extreme cases, hypo- or hyperthermia may result.

In conclusion, significant gains can be the result of improving the art of protective cloting, in terms of performance, comfort and safety. Especially, this is valid in the field of working / functional clothing including firebrigade- military and other uniforms, protective wear for factory workers, and protective garment in biologically or chemically dangerous environments, and especially sports wear, especially those designed for extreme conditions. It follows from tables 1, 2 that a flow increase through the garment by one order of magnitude or more is necessary in order to preserve the body fluid management when using protective wear.

However, the driving force of fluid transport for present textiles imposes a limitation on the amount to be transported.

NO 308,095 discloses a method for fluid transport in textiles, where the liquid is forced through the textile by means of a pulsating current applied to conductor or semiconductor layers woven onto, or by other means applied to the textile. The drive mechanism is electroosmosis, i.e. electroosmosis of type 1 (EO1).

As EO1 represents an additional driving force, larger amounts of water can be transported away from the body by this method. Furthermore, it is not depending upon external conditions like temperature and humidity. Representative liquid transport rates are several 100ml / hour.

Also, the technology of drying concrete buildings by means of EO1 have been developed. Very satisfactory results are obtained if the water is relatively pure, and in many cases near optimal humidity conditions are obtained.

However, several technological problems are known for EO1 liquid transport:

Because the transport of liquid is linear with respect to the electric field strength, a direct electric field component must be present in order to obtain directed liquid transport. This results in several electrochemical effects which are undesirable.

Firstly, electrode reactions can result in production of dangerous substances, e.g. Cl_2 gas from electrolysis of NaCl in perspiration. When pure (condensation) water is transported by EO1 water splitting leads to significant pH changes and gas evolution near the electrodes. In addition to being harmful to the human body, the reaction products can alter the electrokinetic characteristics of the system. Thus, the electrokinetic potential of the pores may change, leading to reduced or even reversed flow. Also, the conductivity of the solutions can increase, resulting in large energy losses.

Further, concentration profiles can be established along the pore axis, counteracting the EO1 transport.

Thus, EO transporting systems are often unstable, and occur in the presence of electrochemical reactions. For applications like drying concrete strucures or soil stabilization, some amount of chemical reactions could be allowed. However, the EO textiles should often be used in an environment much more vulnerable to reaction products. Furthermore, the smaller volume of the system increases the influence of reaction products on its performance.

It is an object of the present invention to develop methods, materials and new applications for electrically driven liquid transport omitting the problems associated with prior known solutions. Further, it is an object of the invention to increase the liquid flow velocities, thus providing materials with improved characteristics. The water movement across such materials makes these materials suitable even under extreme physical loads.

As discussed above, a mains object of the present invention is to develop fabric materials which can be used in various types of cloths. However, the materials according to the present invention can be used in a variety of other applications. The materials according to the invention is in general capable of providing liquid transport from one side of the material to the other side, i.e. across the material. It follows that the material in accordance with the present invention thus also can be used for hindering liquid from entrancing into or through said material.

The material according to the invention can for instance be used for liquid or humidity control under many circumstances. This includes breathable walls in buildings and transportation, breathable textiles in furniture, health products, etc, and breathable casing for electronics protection. Several of theses applications are excemplified later in this specification.

DETAILED DESCRIPTION OF THE INVENTION

The invention will now be described with reference to the accompanying drawings.

Figure 1 shows an embodiment of a fabric according to the invention where the conducting means consist of pores with sloping pore walls.

Figure 2 shows an embodiment with straight cylindrical pores.

Figure 3 shows details, cross section of an embodiment with straight cylindrical pores.

Figure 4 shows a sphere – packing geometry.

Figure 5 shows in a cross section, a woven textile, including isolating and electrode layers.

Figure 6 shows the surface of a woven textile.

Figure 7 shows the principle of EO2 on a single conducting particle in some liquid of lower conductivity, and in a strong (according to equation 3) electric field, where the normal field component induces the SCR, while the tangential component results in ion and liquid transport.

Figure 8 shows EO2 flows around a particle, which can be seen to be mainly circular.

Figure 9 shows an electric signal with no DC component according to the invention.

Figures 10 to 13 shows regions of electric field strengths for obtaining EO2, where E_min_WS is the minimum E for avoiding water dissociation (equation 5), E_max_SCR_flux (equation 4) or E_max_thin_SCR (equation 6) the upper limit of E for obtaining EO2, E_min_EO2 (equation 3) is the minimum field strength for obtaining EO2, while E_lower_EO2 is four times this, indicating the lower field strength were EO2 is significantly faster than EO1. The field strengths are plotted as function of ion concentration in the water with dissolved NaCl, for different particle sizes. Figure 10, particle size a = 10 μm; Figure 11, particle size a = 100 μm; Figure 12, particle size a = 1 mm and figure 13, particle sizes a = 1, 10, 100, 1000 μm in one figure.

Figure 14 shows hydrodynamic time constant as function of concentration, for different particle sizes a (equation 9).

Figure 15 and 16 shows example results for a fabric material in accordance with the invention.

Figure 17 shows an application where the fabric is used for collecting water from humid air.

Figure 18 shows an application where the fabric is used for filtering contaminated water.

Definition of terms used in the specification and claims

Fabric material: stiff or flexible material consisting of one to several thin layers, and which surface dimensions are larger than its thickness.

Smooth surface: By this should be understood that surface irregularities should be less than 5% of d_{char}, preferably less than 1% of d_{char}.

Characteristic diameter d_{char}: The dimension of the conducting means measured normally to the fabric surface plane. E.g. the diameter of conducting spheres in a monolayer of speres, or the thickness of a porous conducting membrane. For a number of conducting particles contacting each other in the direction normally to the fabric surface plane, d_{char} is taken to be the whole length of the resulting conducting structure, measured in said direction.

Characteristic radii a_{char}: 0.5 times d_{char}.

Pore size: This is defined as the pore diameter, or the mean pore diameter for pores where the diameter is varying along the pore length.

Figure 1 shows and embodyment of a fabric 10 with conducting means 12 shaped as a membrane with varying pore size along its thickness, so that the pore walls are smooth and inclined with respect to an electric field applied normally to said fabric 10. Also shown are porous conducting layers 16, to which an electric signal can be applied, and non – conducting porous layers 14 between the membrane 12 and said electrodes 16, preventing direct contact between the electrode and membranes. An absorbing layer 18 is placed onto the electrode on the side of drying. The conducting means has a thickness of d_{char}, measured normally to the fabric surface (and thus in parallel to the imposed electric field). Alternatively, the absorbing layer 18 could be omitted, or other layers could be added outside the electrodes.

Figure 2 shows an alternative embodiment of a fabric 10, with a conducting means 12 shaped as a membrane with cylindrical straight pores of length d_{char}. The non – conducting layers 14 are constituting part of the same physical membrane. Porous electrodes 16 are also shown.

In figure 3 are displayed details of the fabric shown in figure 2, where the imposed normal electric field strength is shown, in addition to the direction of the local electric field in the pores.

An embodiment with a conducting means 12 of spherical shape is shown in figure 4. Also, porous non – conducting layers 14 are shown in the figure.

An embodyment of a fabric with conducting means shaped as smooth cylindrical fibres in a woven structure, is shown in figure 5. Non - conducting thinner fibres (20) are used in the other weaving direction, in order to fix said conducting fibres at a distance of somewhat less than a_{char} from each other. Non conducting porous layers 14, as well as porous electrodes 16 are also shown.

In figure 6 is shown a top view of the woven layer containing the conducting means 12 and non – conducting material 20 as displayed in figure 5.

The fabric 10 of the present invention can constitute all the layers of the application (textile, casing etc), or it can be incorporated as part of a multilayer structure, e.g. by being laminated to the inside of the outer fabric in a piece of clothing. Also, either part of or the whole application area can be equipped with the fabric material. E.g. a jacket could contain small fabric areas on the back and on the sides, with an ordinary waterproof fabric constituting the rest of the area.

In all structures shown in the figures 1 to 6, porous electrodes 16 with a flow resistance in the same order of magnitude or smaller than that of the conducting means 12 should be

used. The electrodes 16 should be placed in parallel to the layer constituting the conducting means 12. Additional non – conducting layers 14 with porosities within the same limits as for the electrodes 16 could be placed between the electrodes 16 and the conductive means 12 on none, either or both sides. Any or none of the different layers in the resulting structure could be laminated or by other means bonded to each other.

Additional porous layers 18 can be added on either or both side of said structure consisting of the electrodes 16 and the layers between them. For many applications, a superabsorbent fabric or other absorbing layer should be used on the side from which water should be removed.

The layers apart from the conductive means layer must not significantly inhibit the liquid flow. This can be fulfilled if the additional layers have pore – sizes in the same order of magnitude as the layer comprising the conductive means. Alternatively, a higher flow resistance can be allowed for these layers if they are not fixed in a very short distance to the conducting means 12, thus water can accumulate between the layers.
In an alternative embodiment, further consecutive layers 12, 14 can be present between the electrode layers 16.

The embodiment shown in figures 1 to 3 can be produced from a non - porous ion – exchange- or otherwise conducting membrane. Onto each side of the conducting means 12, preferably non – conducting layers are deposited. This can be done by coating, or other membrane production technique. Also, the non – conducting layers could be produced by applying some treatment (chemical or plasma treatment or other) to the conducting membrane rendering it non – conductive in some depth. Finally, straight cylindrical pores are made using a technique such as track – etching, radiation or some mechanical treatment. The pore length axis should be normal or approximately normal to the membrane surface plane. The pore – walls should be smooth. The characteristic diameter d_{char} should be measured as the thickness of the conducting part of the resulting composite membrane. The pore diameter should be below 2 a_{char}, and preferably be between1/8 – 0.5 a_{char}. The thickness of the isolating layers should be smaller than d_{char},

preferably between 0.1 and 0.5 d_{char}. As the electric field imposed normally to the membrane by the electrodes will deviate towards the highly conducting walls, there will be both normal and tangential field components to the walls. Thus, EO2 conditions originates, which for said geometrical relations will lead to directed water transport.

Still another membrane geometry is the monolayer sphere – packing structure depicted in figure 4. Preferably, the spheres should be fixed at a distance in said optimal distance interval, by adhering them to a non – porous layer. If more than one particle layer is used, either the particles in each layer or in adjacent layers must be kept at a distance in said interval, otherwise no directed transport would be obtained.

The conductive layer could also be a woven structure, as shown in the figures 5 - 6. Conducting fibres, e.g. ion exchange fibres of smooth circular cross – section should be used in at least one weaving direction. Any yarn of a chosen cross section could be used in the other direction, in order to fix the conducting means at distances in said interval (smaller than 2 a_{char}, preferably between 1/8 to 0.5 a_{char}).

The underlying theoretical concept for the invention is so called "electroosmosis of the second kind" (EO2) or "superfast electroosmosis". A number of conditions have to be fulfilled in order to obtain EO2, especially if directed transport shall be obtained.

Liquid transport by EO2 is 10 – 100 times faster than for classical electroosmosis (EO1) applying the same electric field strength E. Compared to EO1, the same speeds can be achieved by using the square root of E. This makes it possibel to lower E, thus reducing or eliminating the problem of electrochemical reactions. Also, very high liquid flows can be obtained.

Being non – linear in the electric field strength, EO2 also makes it possible to obtain directed liquid transport using an alternating electric field, with little or no direct field component. Thus, the stability problems mentioned above can be reduced or eliminated. In addition, electrode reactions (including electrode gas evolution) will also be reduced or

eliminated in an alternating field, as the polarization current will be larger, and the faradayic current smaller (or zero) for alternating fields.

The concept underlying the invention will be explained with reference to fig. 7. First, EO2 in general will be treated, followed by a descriptions of the special conditions under which directed EO2 pumping is obtained, more particularly, how this can be obtained in a fabric. EO2 is realized near the surface of a (ionically, electronically or hole-) conducting material surrounded by a liquid of lower conductivity, if there exists an electric field with both components normally and tangential to the surface, the strengths of the field components being in a certain interval, dependent on the system geometry and composition. One example is a spherical conducting particle placed in the water – filled space between two parallel electrode planes (fig. 7), where the electric field can be decomposed in the two said components E_{tan} and E_{norm}. The normal component results in concentration polarization near the surface. When E_{norm} is strong enough for the over limiting current regime to be reached, a space charge region (SCR) appears near the surface. This zone has properties similar to the electric double layer (EDL) present at most surfaces in contact with a liquid, and which is responsible for the phenomena of EO1. However, the SCR potential is 10 – 100 times stronger than the EDL potential, thus the flow velocity is larger by the same factor.

The EO1 velocity is given by the Smoluchowsky equation,

Equation 1

$$v^{EO1} = \frac{\varepsilon \zeta E_{\|}}{\eta}$$

Here, is the liquid permittivity, the surface (zeta) potential of the wall, $E_{\|}$ the electric field strength parallel to the charged surface, and the liquid viscosity. For EO2, the velocity is given by the formula

Equation 2

$$v^{EO2} = \frac{2\varepsilon a_{char} E_{\parallel} E_{\perp}}{\eta}$$

E being the normal electric field component.

The characteristic size of the conducting particle / material is be defined as $d_{char} = 2a_{char}$, where a_{char} is the particle radii. In the case of other shapes of the conducting particle, d_{char} is taken to be the dimension measured in the flow direction. The SCR charge is approximately equal to d_{char} times E.

Classical electroosmosis (EO1) is caused by transport of permanent charges (ions) in the EDL. These ions are hydrolyzed (i.e. a number of water molecules are associated to each ion) or in general solvated (other solvent than water may be used). When the electric field sets the charges in motion, water is also transported. While this effect is taking place in a thin charged zone, the whole pore – liquid is set in motion by viscous forces. The water transport is proportional to the EDL (or zeta-) potential and E.

It is important that the SCR is established independently of the presence of any EDL on the surface. The notion of "electroosmosis of the second kind" indicates the similarity to EO1 by having its source in a thin charged zone, which is different from electric effects working on the bulk liquid (the latter is termed electrohydrodynamic effects).

An SCR is induced on the conducting surface if the field is strong enough to give a strong concentration polarization. The polarization zone then consists of a diffusion zone at the boundary with the bulk liquid, the SCR layer closer to the conducting surface, and possibly an EDL closest to the surface. Such polarization phenomena have been described for both ionically and electronically conducting materials.

The polarization phenomenon can be described most simply with reference to a permselective (cat)ion conducting material in some liquid of lower conductivity. This

phenomenon is well known, and will be described briefly here. By directing an electric field towards the membrane, cations are transported towards and through the solid material, while no anions are allowed to pass in the opposite direction, due to permselectivity. At steady state, the electrodiffusional flux of co-ions away from the membrane is compensated by a diffusional flux in the opposite direction. Thus, a diffusion zone with concentration decreasing towards the membrane is observed. Upon increasing the electric field strength, the current increases while the concentration decrease becomes larger. A limit is reached at zero ion concentration near the membrane. At this point, no current increase is observed upon further increasing the voltage, thus the term "limiting current".

However, while the limiting current represents a plateau in the voltage – current curve, a further increase in current takes place if the voltage is high enough. One feature of this strong concentration polarization, is the appearance of the SCR close to the membrane (between the membrane and the diffusion zone).

One reason for the appearance of over limiting current, is the appearance of EO2 eddies (circular flows, sometimes referred to as electroconvection) in the polarization zone, adding to the diffusional ion transport. Even at a flat membrane, EO2 eddies are observed.

In electromembrane processes, high currents at lowest possible voltage is desired, as this gives a more energy efficient process. Thus, it has been an objective of some studies to increase the EO2 convection in electrodialysis by special membrane and stack design (see examples below).

In the following, the mechanism will mainly be described with reference to the spherical particle. However, the extension to other geometries is straightforward, as the description in terms of a_{char} can be used for all shapes.

The underlying concept of the invention, is that the tangential electric field component works on the SCR induced by the normal component. The solvated ions in the SCR are then transported similarly to the ions in the EDL for classical EO. In both cases, the bulk pore liquid is set in motion due to viscous forces.

The conditions for obtaining EO2 can be summarized:

1. A conducting media with both tangential and normal electric field components to its surface is surrounded by a liquid of lower conductivity.

2. A (normal) potential drop which is large enough for inducing the SCR must be present. This means that the dimensionless potential drop across one characteristic particle diameter is larger than unity, which translates into:

Equation 3

$$E > 0.013V / a_{char}$$

3. The tangential field component must not be too large, otherwise the SCR are depleted of ions, and the SCR becomes thinner. Thus, the electric potential should not exceede:

Equation 4

$$E_{\max\_SCR\_flux} = \left(\frac{3}{2}\right)^{\frac{4}{5}} \frac{RT}{F} m^{-\frac{2}{5}} \kappa^{\frac{4}{5}} a_{char}^{-\frac{1}{5}}$$

Here, R is the gas constant, T the temperature, F Faraday's constant, m a dimensionless constant equaling 0.2 for aqueous solutions, and the inverse Debye – length.

4. The conducting media could be conducting by means of ions, electrons or holes; and it could be a conductor or semi – conductor. It should preferably be non – porous, but could also be porous, although this would lead to a reduced velocity. The best results are

obtained for a permselective ion – conductor. While the conducting material is not porous in itself, it must constitute the solid matrix (or part of such) for a porous structure.

5. In order to avoid water splitting, the concentration in the SCR should exceed the ion – product of water. As EO2 convection is counteracting the lowering of concentration resulting from polarization, a lower electric field strength above which no water splitting is present is observed:

Equation 5

$$E_{\min\_WS} = \frac{3}{8\sqrt{2}} m^{-1} \left(\frac{k_w}{c}\right)^3 \frac{RT}{F} \kappa^2 a_{char}$$

where $k_w = 10^{-7}$ M is the dissociation product of water, and c the liquid ion concentration.

In addition comes the condition of thin SCR, which is fundamental in the theory of EO2. This is given by the expression:

Equation 6

$$E_{\max\_thin\_SCR} = \frac{2}{9} \frac{RT}{F} \sqrt{m} \kappa^2 a_{char}$$

From these conditions, an interval of electric field strengths for which EO2 will appear, can be calculated for a certain system. This interval depends upon ion concentration and particle size among other things, as can be seen from equations 3 - 6. The calculated critical field strengths are plotted in figures 10 – 13.

As a result of the dependencies upon both the normal and tangential field components, the liquid velocity is non linear in the electric field strength. For this reason an alternating

field can be applied (illustrated in 9), contrary to for EO1. For EO2, the velocity is approximately proportional to the square of the field strength (equation 2).

The conditions described above have to be fullfilled in order to obtain the phenomena of EO2. However, in most systems were these conditions are fulfilled, still no directed bulk liquid transport is obtained. No liquid transport is achieved across the fabric material. Instead, circular or eddie flows are obtained inside the pores or on the membrane surface.

For various reasons, systems known from the prior art will not give any directed liquid transport by EO2. Firstly, the phenomenon occurs on the surface of a non porous membrane. Any directed EO2 transport would be hampered by this membrane. The reduction in liquid velocity caused by any membrane which the flow must be pumped through, could be calculated by multiplying the velocity by the following correction constant

Equation 7

$$C = 1 - \frac{1}{1 + \dfrac{\lambda_{passive} d_{passive}{}^{2}}{\lambda_{active} d_{active}{}^{2} \dfrac{\Delta x_{passive}}{\Delta x_{active}}}}$$

Here, the indices passive and active refers to the membrane and the EO2 pumping layer (were some directed transport is assumed to be present), is the porosity, d the pore sizes and x the thickness of the layers. It can be seen that the corrected EO2 transport is zero for non porous membrane ($d_{passive} = 0$).

Secondly, directed EO2 transport is only obtained for certain configurations of conducting particles or other conducting structure, as described above.

Thus, the only mechanism for liquid transport through conventional known fabrics, is by EO1. The effect of EO2 eddies on the membrane surface, is to decrease the thickness of

the diffusion layer (because the EO2 convection adds to the diffusion). As a result, a larger part of the total electric potential drop occurs across the membrane (and a smaller part in the polarization zone), giving a larger useful ion transport with concomitant EO1. Thus, the EO2 eddies on the surface indirectly leads to a larger EO1 transport through the membrane, as a smaller part of the potential drop is wasted on a low conducting polarization region.

In this manner, the ion and EO1 transport increases up to a few times (as opposed to the much larger velocity for EO2 liquid transport), and of course, none of the advantages of EO2 water transport can be obtained for this system.

The additional conditions for directed EO2 liquid transport according to the present invention are as follows:

1. There should be no non – porous layers adjacent (in the flow direction) to the layer including the conducting means.

2. The conducting means surface must be very smooth, otherwise no directed EO2 transport are obtained (circular flows could appear). By this should be undestood that surface irregularities should be less than 5% of d_{char}, preferably less than 1% of d_{char}.

3. For spheres, the flow pattern in 8 is observed. This means that the flow will be reversed at a certain distance from the sphere. Thus, there should only be a limited window close to the conducting means which is available for liquid flow, and this determines the distance between the conducting particles, and between the conducting particles and other solid materials, e.g. the channel walls. It was found from experiments that the particles should be kept at a distance of below and $2a_{char}$, preferrably between 1/8 and ½ a_{char}, in order to obtain a large directed flow.

Some structures not pertaining to this, e.g. a monolayer of conducting granules could also be used, but this is less preferable, as the flow would be reduced A packed structure of more than one layer, could not be used, as only circular flow would be obtained by EO2.

4. For other shapes of conducting means, the structural properties should be similar. Thus, the conducting particles should be kept at a distance between 1/8 and ½ of their characteristic dimensions a_{char}, as defined in this text.

ELECTRIC SIGNAL

The electric signal produced by the electrical connection means 16 can consist of an alternating voltage with square- triangular- sawtooth- sine- or other shape. The frequency must be below the hydrodynamic frequency, as illustrated in figure 14. Thus, a_{char} = 1mm gives f_max = 1Hz, a_{char} = 100 µm gives f_max = 100 Hz, and a_{char} = 10 µm gives f_max = 10 kHz. A frequency ten times lower than this theorethical maximum should be used, in order to obtain a significant period of flow in each pulse.

For symmetrical conducting means geometry, the signal should preferably have a duty cycle, and more preferably a duty cycle of 29%, meaning that the strong pulse (which should have the polarity giving EO2 flow in the desired direction) should have a duration of 29% of the signal period. When using a duty – cycle, the signal should preferably have an offset, which is chosen so that the average signal direct component is zero.

For conducting means with a broken symmetry (e.g. figure 1), a symmetrical alternating signal could be used (square- triangular- sawtooth- sine- or other shape).

For applications where electrode reactions are not a problem (e.g. when short operating time), a direct voltage component or a pure direct voltage could be used.

Preferably, the electric power should be delivered in the potentiostatic regime, which gives the fastest polarization.

The signal could also be interrupted by a pause with no signal, which could occur for every N cycle of the signal, N being a number equal to or larger than one. The signal should be controlled by an electronic device (microchip or computer), and it could be automatically or manually changed and controlled during operation. This could be done based on information of the system performance obtained from the system microsensors.

Preferably, the signal frequency should be chosen to be higher than the inverse electrode polarization time,

Equation 8

$$t_{pol\_el} = \frac{L}{\kappa D}$$

where L is the distance between electrodes,   is the inverse Debye length (inverse EDL thickness), and D the diffusion coefficient of current carrying ions.

If an alternating or pulse electric signal should be applied, the maximum frequency is determined by the hydrodynamic time constant,

Equation 9

$$t_{HD} = \frac{a_{char}^{2}}{\nu}$$

where   is the kinematic viscosity of the liquid.

MATERIALS

Generally, any electron-, ion- or hole conductor could be used as the conducting means, as long as its conductivity is at least 10 times that of the liquid which should be

transported. Example materials includes doped silicone and other semiconductors, metals, ion – exchanger such as sulfonated polystyrene crosslinked with divinylbenzene (PS-DVB), conducting polymer (e.g. doped polyaniline (PANi), polyethylene or other doped polymer), carbon, graphite, or a polymer filled with some of said conducting materials.

If the conducting means is a membrane, a specially developed membrane could be produced by any technique such as phase – inversion techniques, coating, extrusion or other. The pores could be made by post processing of a non – porous membrane, as described above.

For sphere – packing structures, a monolayer could be made by sintering ion – exchanger or other particles to form a membrane, using heat or chemical or physical treatment, or a combination of such treatments, like hot – pressing. The monolayer could also be produced by flocking techniques, where the conducting particles are deposited onto some porous support, using a small amount of binder.

For a woven conducting structure, ion – exchange fibres could be used as the conducting means. The conducting fibres could also be made from any of said conducting materials. Monofilament conducting yarn with a smooth circular cross section should be used (e.g. carbon fiber, doped polyaniline or other conducting polymer).

The electrodes 16 constitutes additional porous layers, which could be made from any of said conducting materials, apart from those with ionic conduction. Examples include: metal grids; woven or non – woven fabric from multifilament yarn, containing one or more metal (or carbon or other conducting) filaments; carbon cloths; woven or non – woven fabric of conducting polymer, which is made conducting by either filling it with some conducting particles (carbon or metal or other), or is made inherently conducting by doping (e.g. doped polyaniline); porous membrane or textile layer which is impregnated or coated by some conducting polymer (doped polyaniline, filled polymer etc); porous membrane or textile layer which is made conducting by printing with conducting ink;

porous membrane or textile layer which is made conducting by some chemical or physical post treatment (e.g. doping, plasma treatment).

If only one side of the electrode fabric is made conducting (e.g. by impregnating this side by the conductor), the other side could provide isolation for avoiding direct contact with the conducting means, thus eliminating the need for additional insulating layers.

The electrode 16 on the side of drying could also serve as an absorbing layer, e.g. a superabsorbent could be bonded to the electrode. Similaraly, the electrode material could have properties allowing it to serve as a strenghtening, water repellent or other traditional functional part of the textile.

If necessary, inert porous layers 14 could be introduced between the conducting means and electrodes, in order to avoid direct electrical contact. Any porous fabric could be used for this purpose. The porous inert layer could also be made by coating.

The EO2 textile consisting of electrodes and the layers between them, could be combined with more layers in the application. In many applications, an absorbing layer, e.g. superabsorbent textile, should be added to the side of drying.

The power supply can be electric supply mains, batteries, fuel cells, solar cells, generator or other. For wearable and portable applications, power generatiors based on small temperature differences or body movement could be used. An electronic control unit should be connected to this in order to apply the correct signal. This unit could receive data from humidity, temperature or other sensors. In this manner, the signal can be adjusted in response to changing humidity content, and be shut off when needed.

EXPERIMENTAL RESULTS

Figure 15 and 16 demonstrates the possibility of transporting water by means of EO2 across a fabric according to the invention, and furthermore it demonstrates the possibility

of transporting water against a pressure gradient imposed by a water pressure on the side of the fabric to which water is pumped.

The graph shows pressure driven transport (o), in addition to total water transport under conditions of EO2 directed in parallel (+) or antiparallel (-) to the pressure driven transport.

The experiment was performed by exposing one side of the fabric to normal ambient conditions, while there was a water level of 10 cm on the other side. Total water transport (liters / m^2 hour) was measured at different times from the experiment start, under conditions:

1. No electric signal, thus only pressure driven transport is present.
2. Electric signal giving EO2 transport parallel to the pressure driven transport, thus the measured water transport is the sum of EO2 and pressure driven transport.
3. Reversing the electric signal, EO2 and pressure driven transport works in opposite directions.

The conducting layer 12 consisted of cylinders with diameter 20 μm and length 300 μm (carbon fibers), which constituted a porous conducting layer. Porous synthetic membrane filters 14 was used, and metal grid electrodes (100 mesh / inch) 16. The structure was fixed by means of a mechanical pressure. A higher pressure was used in the experiment represented in figure 15.

A square pulse signal with no direct field component as shown in figure 9 was applied.

Fig 15: The field strength in the strong pulse was 50V, while the duty – cycle was 20%, frequency 10 Hz.

The resulting EO2 transport is in the order 30 l / m^2h, and total drying out on the ambient membrane side was achieved. The experimental results clearly indicates that very large transport rates, as well as complete drying against a pressure gradient, can be achieved.

Fig 16: The field strength in the strong pulse was 90V, while the duty – cycle was 20%, frequency 10 Hz. Large EO2 velocities are obtained, but smaller when pumping antiparallel to the pressure driven flow. This can be explained by interactions between EO2 and pressure driven flow, or by capillary forces in connection to drying out the outer side of the fabric.

The better performance with respect to drying reflected in figure 15, can be explained by the the smaller pore – size resulting from the higher mechanical pressure applied here.

APPLICATIONS

It is clear that the fabric material according to the invention is capable of transporting any amount of perspiration water, and furthermore could be engineered to transport much larger amounts of water if the application demands it.

Generally, the fabric according to the invention could be used in a host of cases where perspiration, rain, groundwater, process water, or other liquids needs to be removed or moved.

In many applications, the fabric according to the invention can be further improved by using an absorbing inner layer, of which a superabsorbent is in many cases preferred. Holding a large amount of water when in equilibrium with humid air, the absorbent serves as a humidity buffer, e.g. in clothing, seats and buildings. However, when its capacity is reached, no more humidity can be absorbed. Combined with the fabric according to the invention, on the other hand, the absorbent can be continuosly drained,

resulting in a relyable system for water absorption and air dehumidification, which could be used in a variety of applications, as given in table 3 below.

Table 3

SPORT

- Clothing
- Shoes
- Tents
- Sleeping bags

DEFENCE

- Uniforms
- Tents
- Shoes
- Electronic equipment
- Storage

INDUSTRY / ENGINEERING

- Storage tents
- Containers
- Electronics
- Geo – textiles
- Runways, roads
- Functional clothing
-

HEALTH

- Bed linings
- Electronic equipment
- Carpets

BUILDINGS

- Walls
- Roofs
- Swimming halls

TRANSPORTATION

- Air – planes
- Ships
- Car – seats
- Containers

OTHER

- Collecting condensation water
- Liquid separation
- Filtration

Below is given examples of further treatment of some of the applications in table 3.

Fabric segments could be incorporated in waterproof garments, e.g. on the side and back of jackets, and under the jacket arms.

In sleeping bags, body condensation water is known to be a problem in cold areas, where a weight increase of 10 – 20 kg have been observed after several days due to ice formation. This problem could be solved by using an fabric sheet according to the invention.

For several reasons, there is an increasing need for better breathability in military uniforms. Thicker body armour and protective layers results in lower heat conduction away from the body. Also, the soldies is carrrying with him an increasing amount of electronical and other equipment, increasing the load to be carried. In addition comes biological and chemical weapons protection, which results in low breathability using the present technology of semipermeable membranes. An fabric according to the invention used as a outher textile could be powered by the same supply as the communication system and other electronics carried by the soldier.

In many areas, clothing and equippment getting wet is causing severe problems in the field. Almost any kind of such equippment could be equipped with the fabric system according to the invention, including clothing, tents and electronics.

At present, equipment like vehicles, tanks and planes are often stored in tents, wheras ovens and fans are used for obtaining proper humidity conditions. This results in a large heat loss to the environment. A much more energy efficient solution would be using fabric according to the invention for tents or tarpaulins, which would make the fans and ovens superfluous.

In addition to the military applications, tents could be used for first aid purposes, as well as for building materials, and any industrial purpose.

For electronic equippment which is used outdoor (e.g. mobile phones), condensation is an frequently encountered problem because of temperature variations. This could in many cases be solved by incorporating a segment of a fabric according to the invention in the casing, with an absorbent inner layer.

Geotextiles with a fabric according to the invention could be used for removing water films from roads and runways, and in other cases where moderate amounts of water should be removed.

Another application is bed linings to be used in hospitals, where body fluids could be transported from the absorbing layer through the fabric layer, to be collected in some reservoir. For first aid purpose, fabrics according to the invention could be useful for keeping patients warm and dry.

Fabric textiles or layers materials according to the present invention cold be used as wall- or roof covering materials, where an outer absorbing layer should preferably be used. After passing throught the fabric material, the water could be transported to the outside or a reservoir by gravity, ventilation, electroosmotically or by other means. Also, the water transport could be directed towards the absorbing layer, when air humidification is desired.

Similarly to in buildings, the fabric materials could be used in walls / roofs etc of cars, planes, ships, trains etc. Also, it could be used in car seats and other seats, for avoiding dampness.

Drinking water is a commodity in short supply in large parts of the world. Even if water is available, this may often be contaminated by bacteria and other particles.

One application of the present invention, is to absorb the contaminated liquid into some absorbent of small pore size, subsequently drying it out by means of the fabric material

according to the invention. Alternatively, larger particles could be removed by directly pumping it through the fabric material. This is shown in figure 18.

This principle can be applied not only for free flowing water, but also to collect water from wet soil or sand. The same principle could be used for other separarations of particles from liquids.

Also, water could be collected from humid air using the (super) absobent in conjunction with the fabric layers. By continuously draining the absorbent by the fabric, this will constantly hold below its equilibrium water content, and more water will be collected from the air. In areas with large temperature differences between day and night (like in many desert areas), very high relative air humidities can occur, with corresponding high absorbent equilibrium humidity content. This application is shown in figure 17.

The fabric according to the invention can also be applied for separating different liquids, based on their different intake / absorption and transport rates. The intake rate of water would be favorable compared to oil using oleofobic and hydrophilic absorbents. Furthermore, the transport velocity will be greatest for the least conducting liquid, due to a higher conducting means to liquid conductivity for this liquid. The separation system can be engineered as a flat membrane or textile separating two chambers, one of which contains the liquid mixture. Upon applying the electic signal, a larger amount of the favoured liquid would be transported into the second chamber. This could contain the same favoured liquid, or some liquid which could easily be separated from this. This method could be useful in a number of cases were standard separation methods does not apply, or is difficult or expensive.

Another application of the fabric according to the present invention, is for drying of foods and other substances.

CLAIMS

1. Fabric material (10) adapted to effect a directional flow of liquid across said material (10), characterized in that said material (10) contains: i) electrical connection means (16) for application of an electric field E across a segment of said material (10), and ii) porous layer comprising conducting means (12) wherein the pore walls of said conducting porous layer (12) are curved, or inclined with respect to the electrical field.

2. Fabric material (10) in accordance with claim 1, wherein the conducting means (12) has the shape of spheres, ellipsoids, or cylinders with circular or elliptical cross section.

3. Fabric material (10) in accordance with claim 1, wherein the conducting means (12) has the form of sloping planes thus forming conducting walls with some angle to the surface plane norm of the fabric.

4. Fabric material (10) in accordance with one of the claims 1 to 3, wherein the conducting means is immobilized in a porous matrix by means of a binding material 20.

5. Fabric material (10) in accordance with claim 1, wherein the conducting means (12) is fibers with spherical cross section and smooth surface.

6. Fabric material (10) in accordance with claim 1 and claim 5, wherein the conducting means (12) constitutes part of a woven or non – woven structure.

7. Fabric material (10) in accordance with one of the preceeding claims, wherein said binding material (20) is a non – conducting fiber.

8. Fabric material (10) in accordance with claim 1, wherein the conducting means (12) has the form of a porous membrane with pore walls with varying cross – section.

9. Fabric material in accordance with claim 1 and claim 8, wherein the pore walls has the form of sloping planes relative to the fabric plane normal.

10. Fabric material (10) in accordance with claim 1, wherein the conducting means (12) has the form of a porous membrane with cylindrical straight pores with smooth pore walls, and that the fabric material (10) further contains non - conducting layers (14) on each side of and constituting part of said membrane, so that the cylindrical pores goes through both layers (12) and (14).

11. Fabric material (10) in accordance with one of the preceeding claims, wherein each non-conducting layer (14) has a thickness smaller than d_{char}, preferably between 0.1 and 0.5 d_{char}.

12. Fabric material (10) in accordance with one of the preceeding claims, wherein the pore size of the layer containing the conducting means (12) is smaller than 2 a_{char}, preferably between 1/8 and 0.5 a_{char}.

13. Fabric material (10) in accordance with one of the preceeding claims, wherein the pore walls are sloping at an angle 0 - 80 degrees relative to the fabric surface plane normal.

14. Fabric material (10) in accordance with one of the claims 1 to 13, wherein the pore walls are sloping at an angle 30 - 60 degrees relative to the fabric surface plane normal.

15. Fabric material (10) in accordance with one of the claims 1 to 14, wherein the particles constituting the conducting means (12) have a size of 0,1 – 5 mm, preferable 10 m to 500 m, measured in the directionn normal to the fabric surface.

16. Fabric material (10) in accordance with one of the claims 1 to 15, wherein any of the layers (16), and layers (14) if present are laminated or by other means adhered to each

other, and that said layers are porous, having a hydrodynamic flow resistance comparable to that of the porous layer including the conducting means (12).

17. Fabric material (10) in accordance with one of the claims 1 to 16, where any of the layers (16), and layers (14) if present have a larger hydrodynamic flow resistance than the porous layer including the conducting means (12), but where the layers having larger hydrodynamic resistance are not laminated or by other means adhered to the layer including the conducting means (12), or any layer adhered to the same said layer including the conducting means (12), thus some space are left open between the layers.

18. Fabric material (10) in accordance with one of the claims 1 to 17, wherein said fabric material (10) further includes an additional layer (18) adhered to one or both electrode and not part of the structure between the electrodes, wherein said layer (18) contains absorbents or superabsorbents materials, or such materials immobilized in a non – woven or other fabric.

19. Fabric material (10) in accordance with one of the claims 1 to 18, wherein said fabric material (10) further contains any additional layers allowing for liquid or vapor transport on each side of the electrodes.

20. Fabric material (10) in accordance with one of the claims 1 to 18, wherein said fabric material (10) further contains additional sequences of layers (12) and (14) between the electrode layers (16).

21. Fabric material (10) in accordance with claim 1, wherein the electrical connection means (16) applies an alternating field.

22. Fabric material (10) in accordance with claim 1, wherein the electrical connection means (16) applies an alternating field which has sine, square, triangular or sawtooth shape, or a combination of said shapes.

23. Fabric material (10) in accordance with claim 1, wherein the electrical connection means (16) applies an alternating field where the signal has an offset resulting in a strong and a weak pulse within the signal period, and also a duty – cycle of preferably 29%, so that the strong pulse lasts 29% of the signal period, and where the offset and duty cycle are tuned to give a zero average direct electric signal component.

24. Fabric material (10) in accordance with claim 1, wherein the electrical connection means (16) applies an alternating field where the signal has an overloaded direct component.

25. Fabric material (10) in accordance with claim 21, wherein the electrical connection means (16) applies an alternating field where the electric signal is applied in the potentiostatic regime.

26. Fabric material (10) in accordance with claim 1, wherein the electrical connection means (16) applies an alternating field with a maximum amplitude in V/mm equal to or larger than an amplitude for which the 10 - logarithm is in the linear interval between -2 and 2, for corresponding a_{char} [µm] for which the 10 – logarithm is in the linear interval between 0 and 3.7.

27. Fabric material in accordance with claim 1, wherein the electrical connection means (16) applies an alternating field with a signal period in seconds equal to or larger than a period for which the 10 - logarithm is in the linear interval between -6 and zero, for corresponding a_{char} [µm] for which the 10 – logarithm is in the linear interval between 0 and 3.

28. Fabric material (10) in accordance with claim 1, wherein the electrical connection means (16) applies a direct electric field.

29. Fabric material (10) in accordance with claim 1, wherein the conductivity of the conducting means (12) is more than 5 times the conductivity of said liquid, or preferable at least 10 times the conductivity of said liquid.

30. Fabric material (10) in accordance with claim 1, wherein the fabric material further comprises one or more non-conducting layers (14), providing isolation between the electrodes (16) and the conducting means (12).

31. Fabric material (10) in accordance with claim 1, wherein the conducting means (12) is made of a material selected from the group comprising ion – exchangers such as sulfonated polystyrene - diviniylbenzene or other, inherently conducting polymer such as doped polyaniline or polyethylene or other, carbon, graphite, metal, doped semiconductor (e.g. silicon) or polymer filled by any of said conducting materials.

32. Fabric material (10) in accordance with claim 1, wherein the electrical connection means (16) comprises electrodes made of inherently conducting polymer such as doped polyaniline or polyethylene or other, carbon, graphite, metal, doped semiconductor (e.g. silicon) or polymer filled by any of said conducting materials.

33. Use of a fabric material in accordance with one of the claims 1 to 32, for the manufacturing of a textile material.

34. Use of a fabric material in accordance with one of the claims 1 to 32 in leisure clothes, sports clothes, working clothes and uniforms, and in equipments such as tents, sleeping bags, bed linings and shoes.

35. Use of a fabric material in accordance with one of the claims 1 to 32 as a protective cover or casing or part of such providing protection for electronic or mechanical equipment, such as mobile telephones.

36. Use of a fabric material in accordance with one of the claims 1 to 32, wherein the fabric material constitutes part of the walls, roofs, floors or other surfaces in buildings, means of transport (planes, cars, ships, trains etc) for providing humidity control.

37. Use of a fabric material in accordance with one of the claims 1 to 32, wherein the fabric in connection to an absorbent is used for air humidification and dehumidification, in connection to air conditioning.

38. Use of a fabric material in accordance with one of the claims 1 to 32, wherein the fabric constitutes an upholstery or cover material for car seats or other seats, or part of such cover material, for removing dampness.

39. Use of a fabric material in accordance with one of the claims 1 to 32, wherein the fabric constitutes a layer in roads or run –ways, for removing water and ice films.

40. Use of a fabric material in accordance with one of the claims 1 to 32, wherein the fabric is used for collecting water from an absorbent layer into a tank.

41. Use of a fabric material in accordance with one of the claims 1 to 32, wherein the fabric is used for filtering particles from contaminated water.

42. Use of a fabric material in accordance with one of the claims 1 to 32, wherein the fabric is used for separation of liquids based on their different transport rates through the fabric.

43. Use of a fabric material in accordance with one of the claims 1 to 32, wherein the fabric is used for packaging materials which should be protected from liquid and condensation, or should be kept at a specific humidity level.

44. Use of a fabric material in accordance with one of the claims 1 to 32, wherein the fabric is used for dewatering or drying materials by encapsulating the material to be treated by the fabric.

45. Use of a fabric material in accordance with one of the claims 1 to 32, wherein the fabric is used for removing water from sludge containing components such as oil and sand.

46. Use of a fabric material in accordance with one of the claims 1 to 32, wherein the fabric is used as the canvas or part of the canvas in storage tents, tarpaulins or carpets.

47. Use of a fabric material in accordance with one of the claims 1 to 32- wherein the fabric is used as geo – textiles.

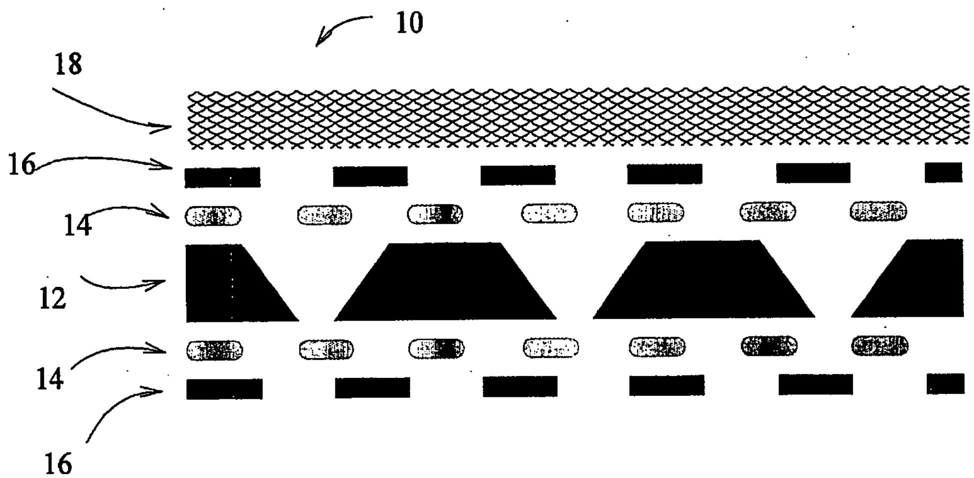


Figure 1

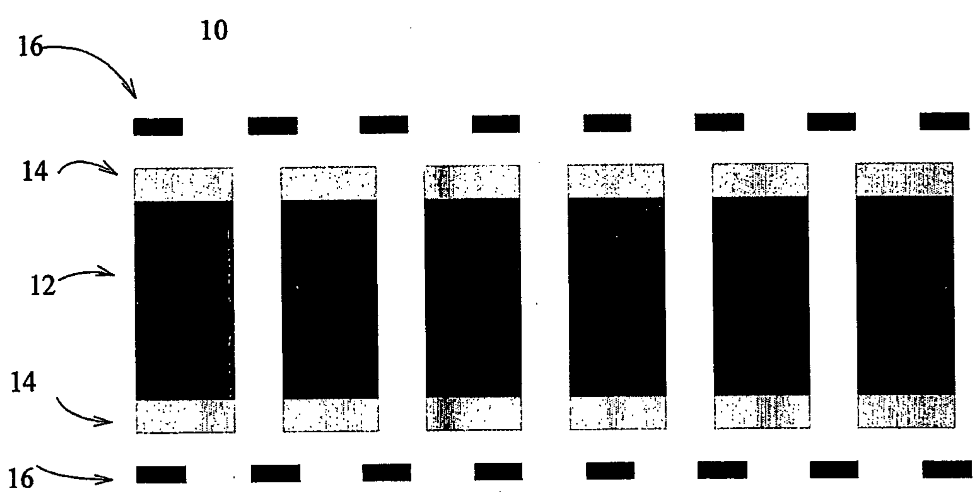


Figure 2

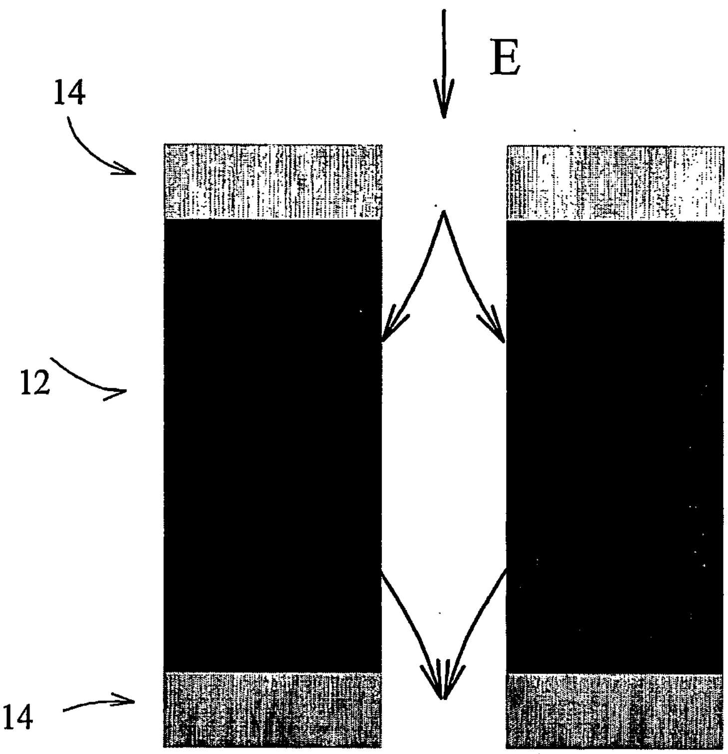


Figure 3

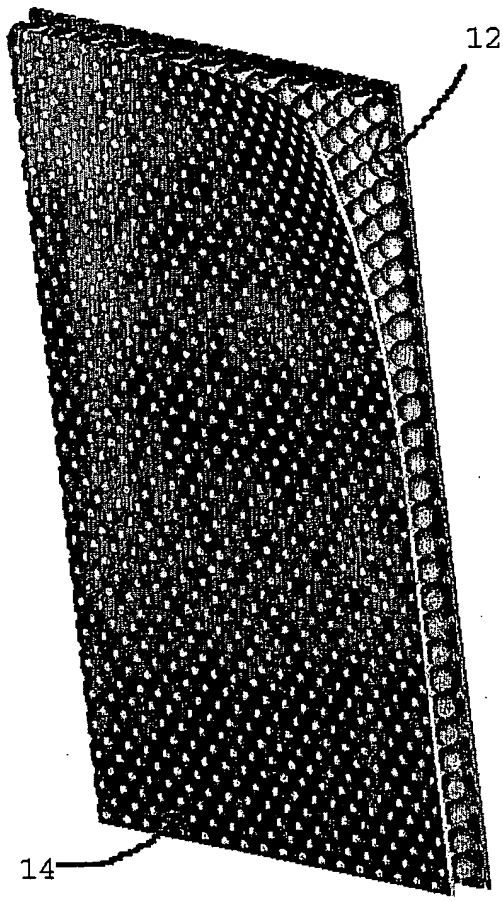


Figure 4

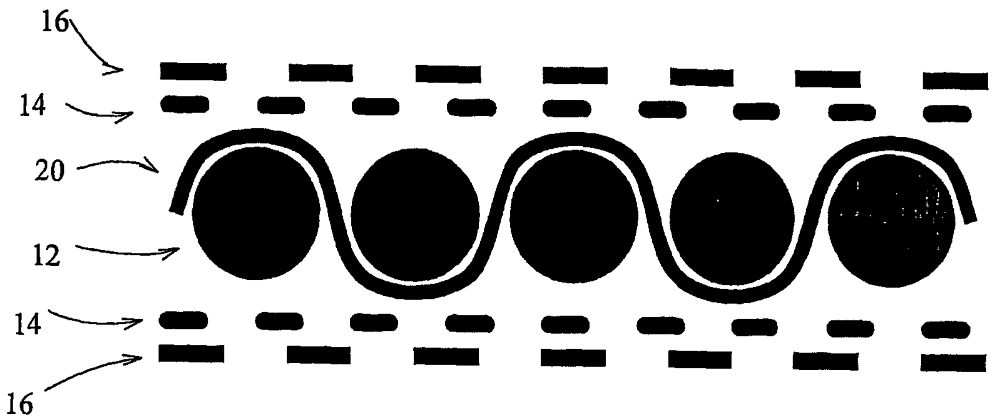


Figure 5

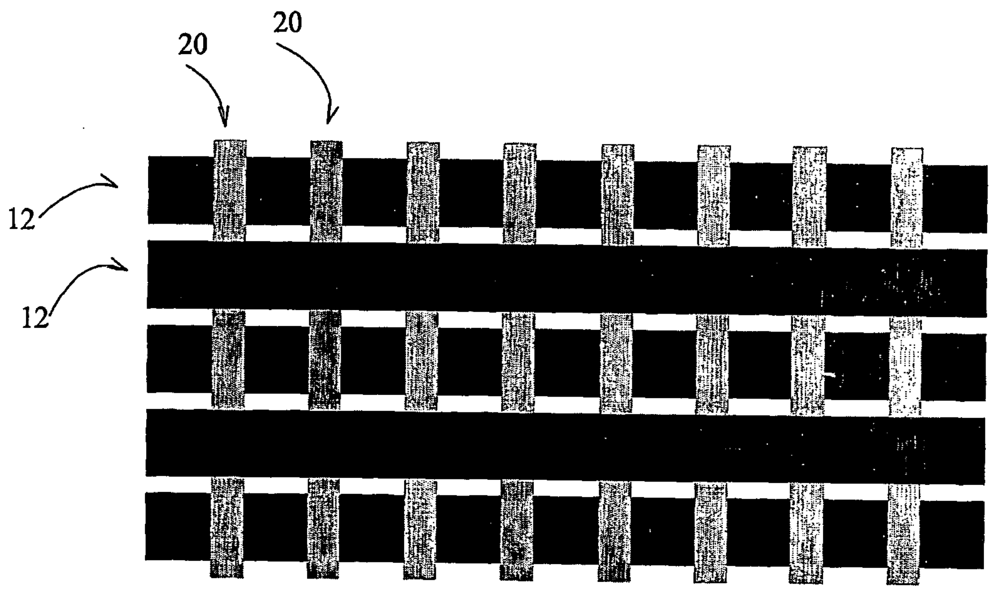


Figure 6

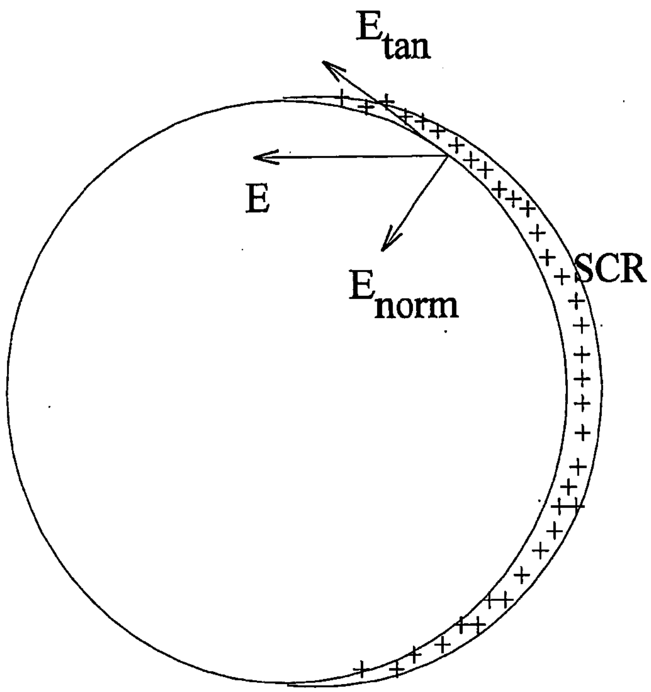


Figure 7

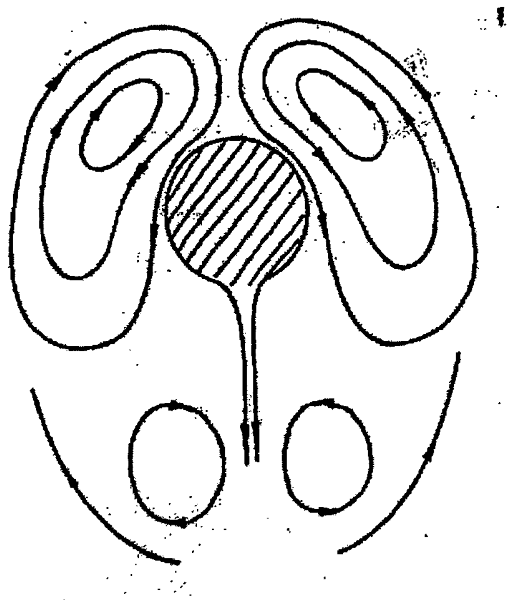


Figure 8

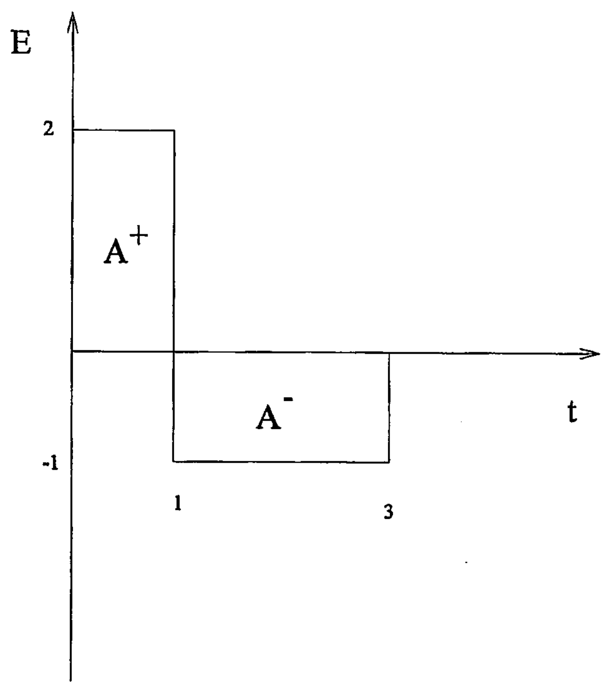


Figure 9

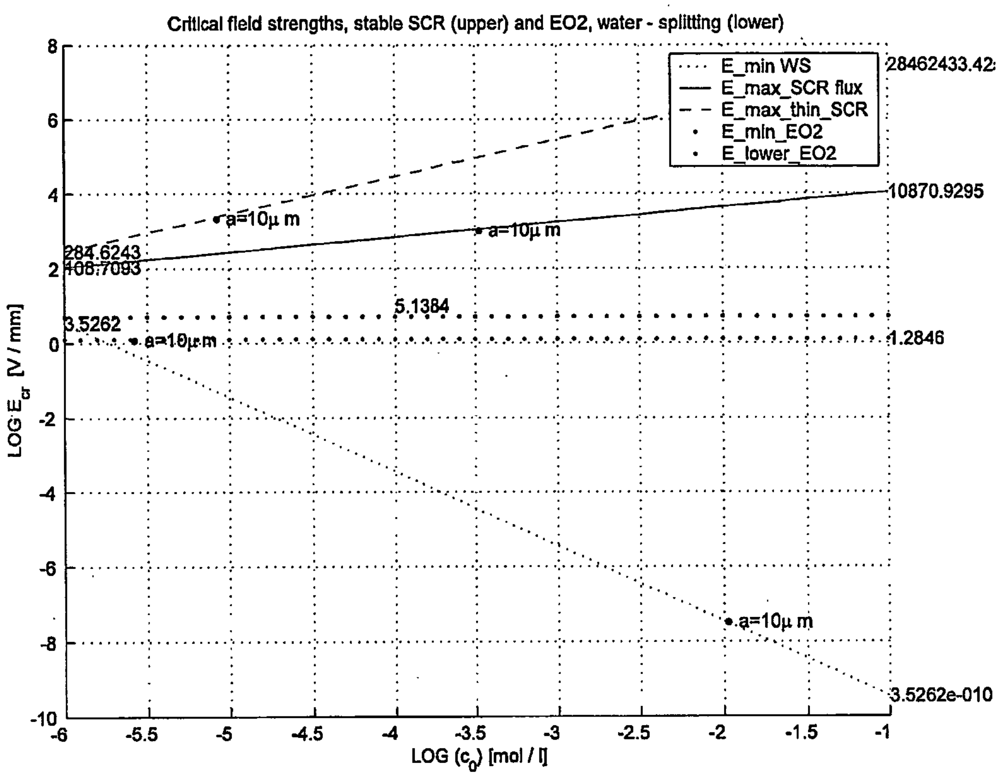

Critical field strengths, stable SCR (upper) and EO2, water - splitting (lower)
E_min WS
E_max_SCR flux
E_max_thin_SCR
E_min_EO2
E_lower_EO2
28462433.42
10870.9295
284.6243
108.7093
5.1384
3.5262
1.2846
3.5262e-010
a=10μ m
a=10μ m
a=10μm
a=10μ m
LOG E_cr [V / mm]
LOG (c_0) [mol / l]
8
6
4
2
0
-2
-4
-6
-8
-10
-6
-5.5
-5
-4.5
-4
-3.5
-3
-2.5
-2
-1.5
-1

Figure 10

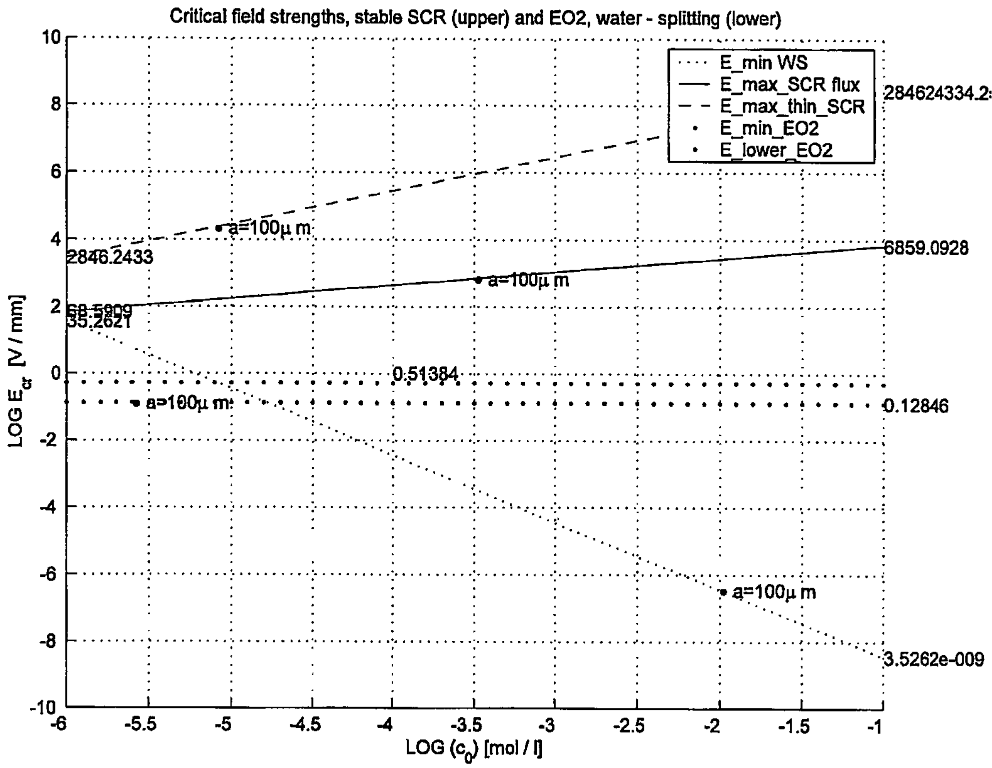

Critical field strengths, stable SCR (upper) and EO2, water - splitting (lower)
E_min WS
E_max_SCR flux
E_max_thin_SCR
E_min_EO2
E_lower_EO2
284624334.2
6859.0928
2846.2433
a=100μ m
68.5909
55.2621
0.51384
0.12846
3.5262e-009
LOG E_{cr} [V / mm]
LOG (c_0) [mol / l]
10
8
6
4
2
0
-2
-4
-6
-8
-10
-6
-5.5
-5
-4.5
-4
-3.5
-3
-2.5
-2
-1.5
-1

Figure 11

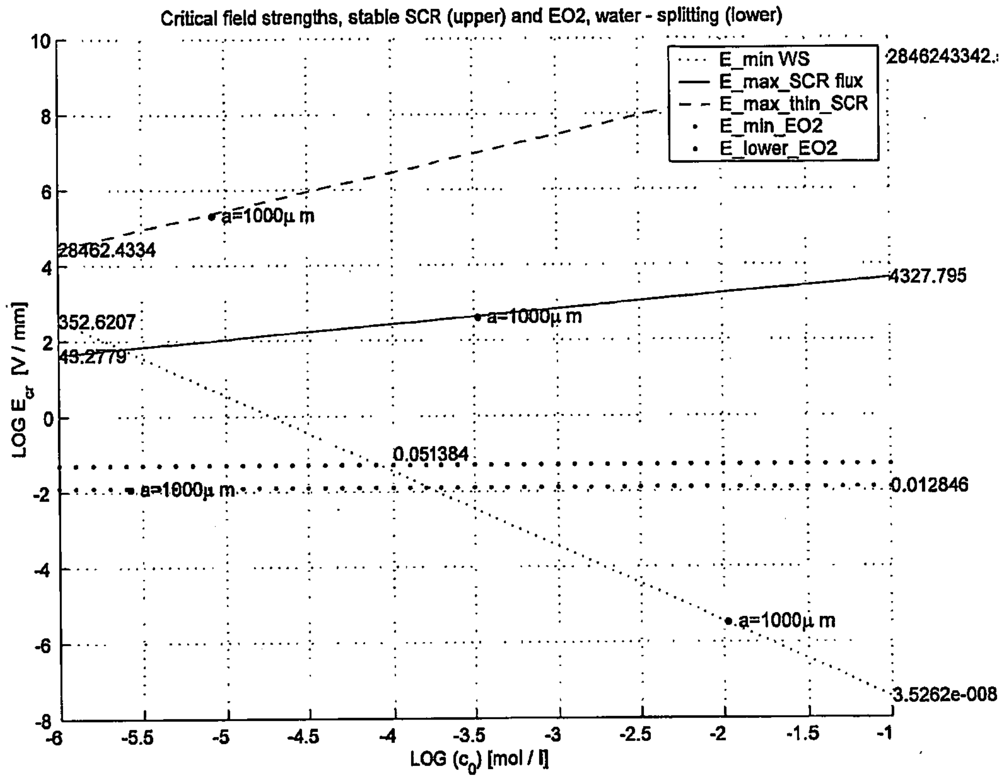
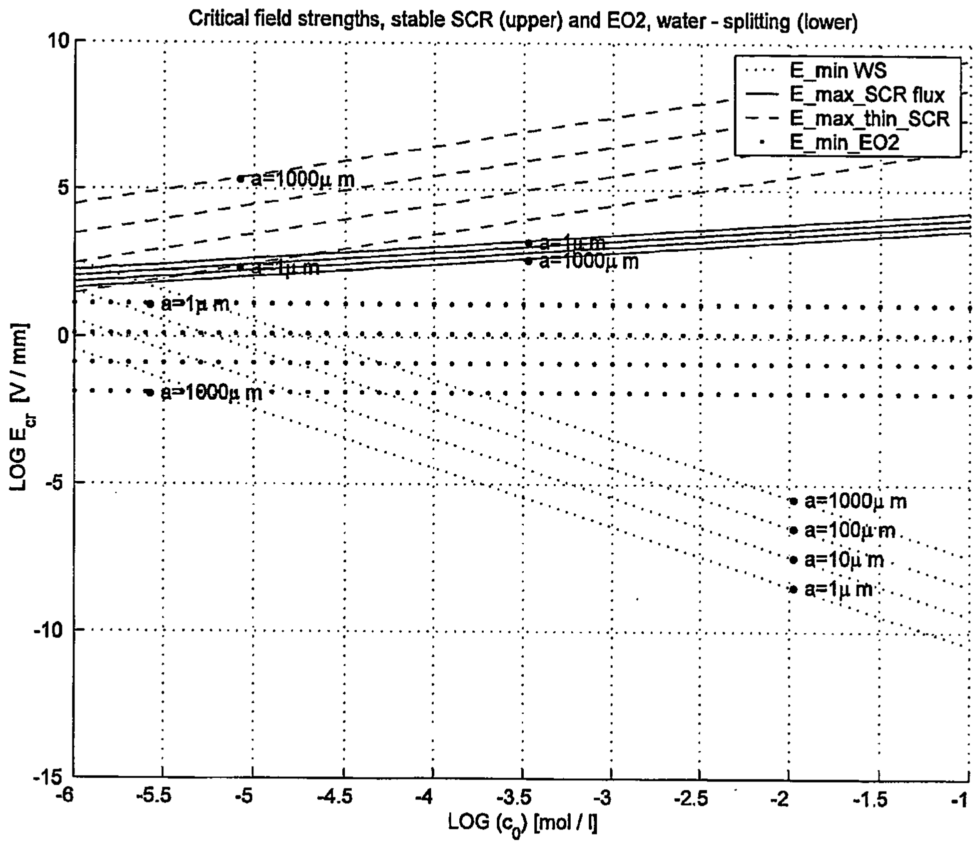

Critical field strengths, stable SCR (upper) and EO2, water - splitting (lower)
E_min WS
E_max_SCR flux
E_max_thin_SCR
E_min_EO2
E_lower_EO2
2846243342.
28462.4334
a=1000μ m
4327.795
352.6207
43.2779
0.051384
0.012846
3.5262e-008
LOG E_cr [V / mm]
LOG (c_0) [mol / l]
10
8
6
4
2
0
-2
-4
-6
-8
-6
-5.5
-5
-4.5
-4
-3.5
-3
-2.5
-2
-1.5
-1

Figure 12



Critical field strengths, stable SCR (upper) and EO2, water - splitting (lower)
E_min WS
E_max_SCR flux
E_max_thin_SCR
E_min_EO2
a=1000μ m
a=1μ m
a=1μ m
a=1000μ m
a=1μ m
a=1000μ m
a=1000μ m
a=100μ m
a=10μ m
a=1μ m
10
5
0
-5
-10
-15
-6
-5.5
-5
-4.5
-4
-3.5
-3
-2.5
-2
-1.5
-1
LOG E_{cr} [V / mm]
LOG (c_0) [mol / l]

Figure 13

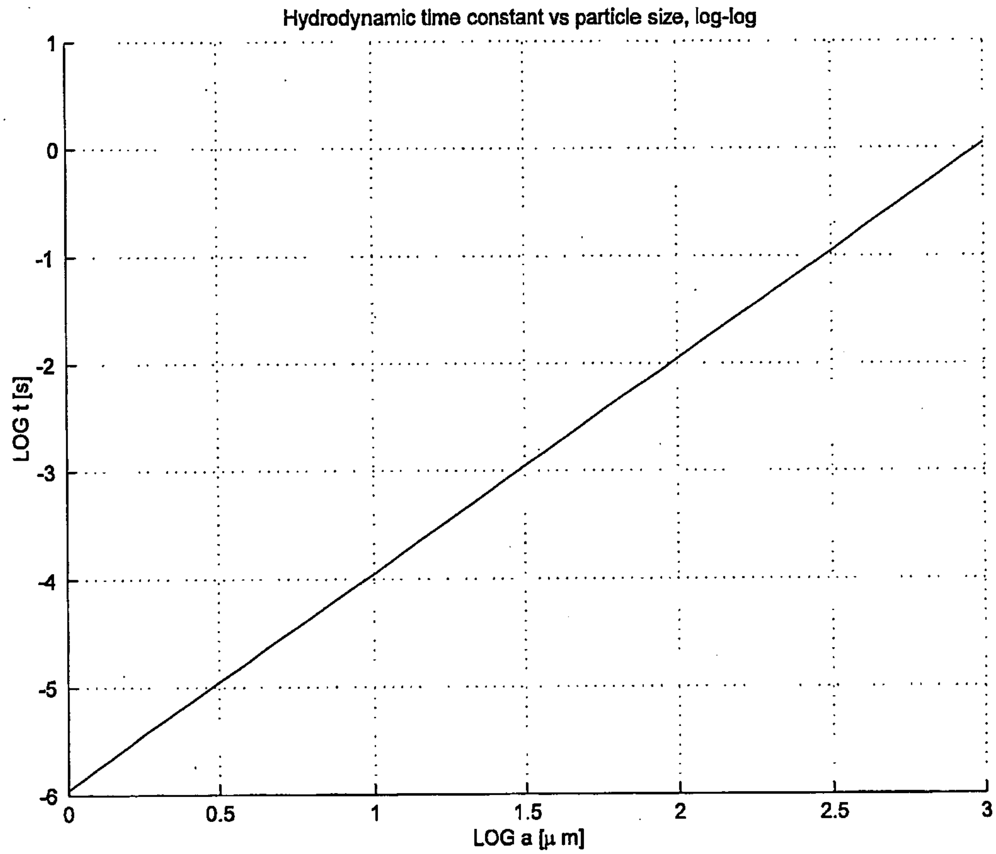

Hydrodynamic time constant vs particle size, log-log
LOG t [s]
1
0
-1
-2
-3
-4
-5
-6
0
0.5
1
1.5
2
2.5
3
LOG a [μ m]

Figure 14

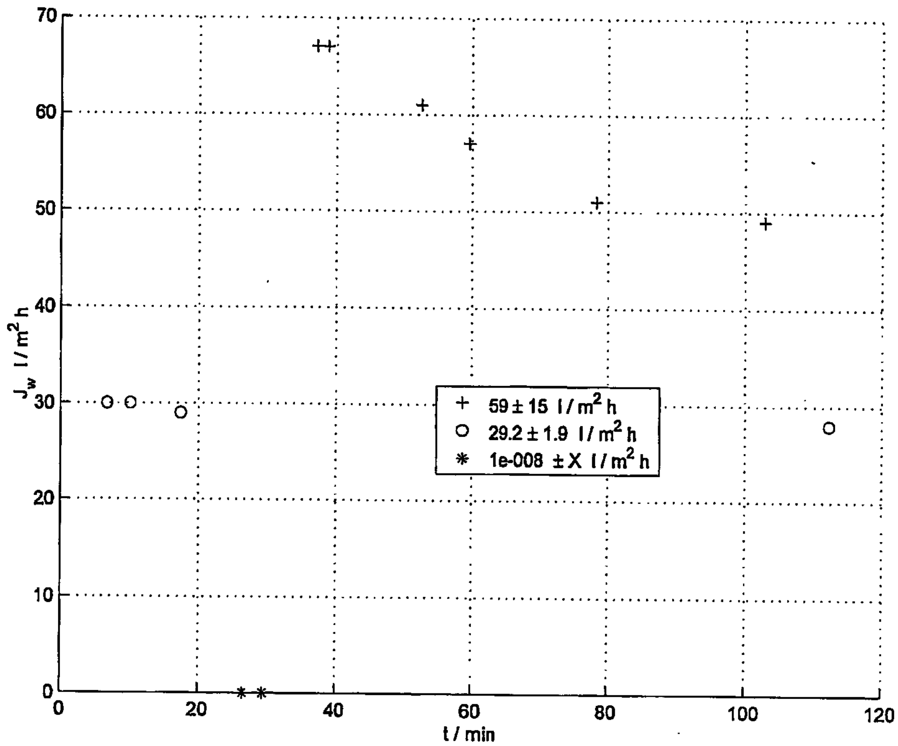

70
60
50
40
30
20
10
0
J_w l / m^2 h
0
20
40
60
80
100
120
t / min
+ 59 ± 15 l / m^2 h
o 29.2 ± 1.9 l / m^2 h
* 1e-008 ± X l / m^2 h

Figure 15

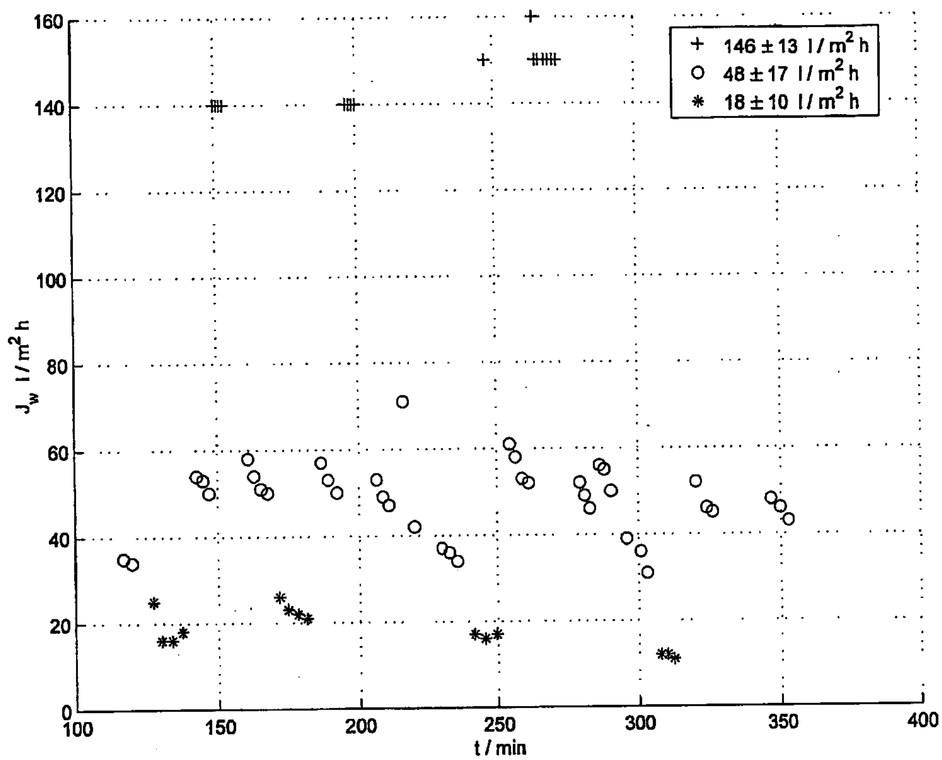

160
140
120
100
80
60
40
20
0
100
150
200
250
300
350
400
J_w l / m^2 h
t / min
+ 146 ± 13 l / m^2 h
o 48 ± 17 l / m^2 h
* 18 ± 10 l / m^2 h

Figure 16

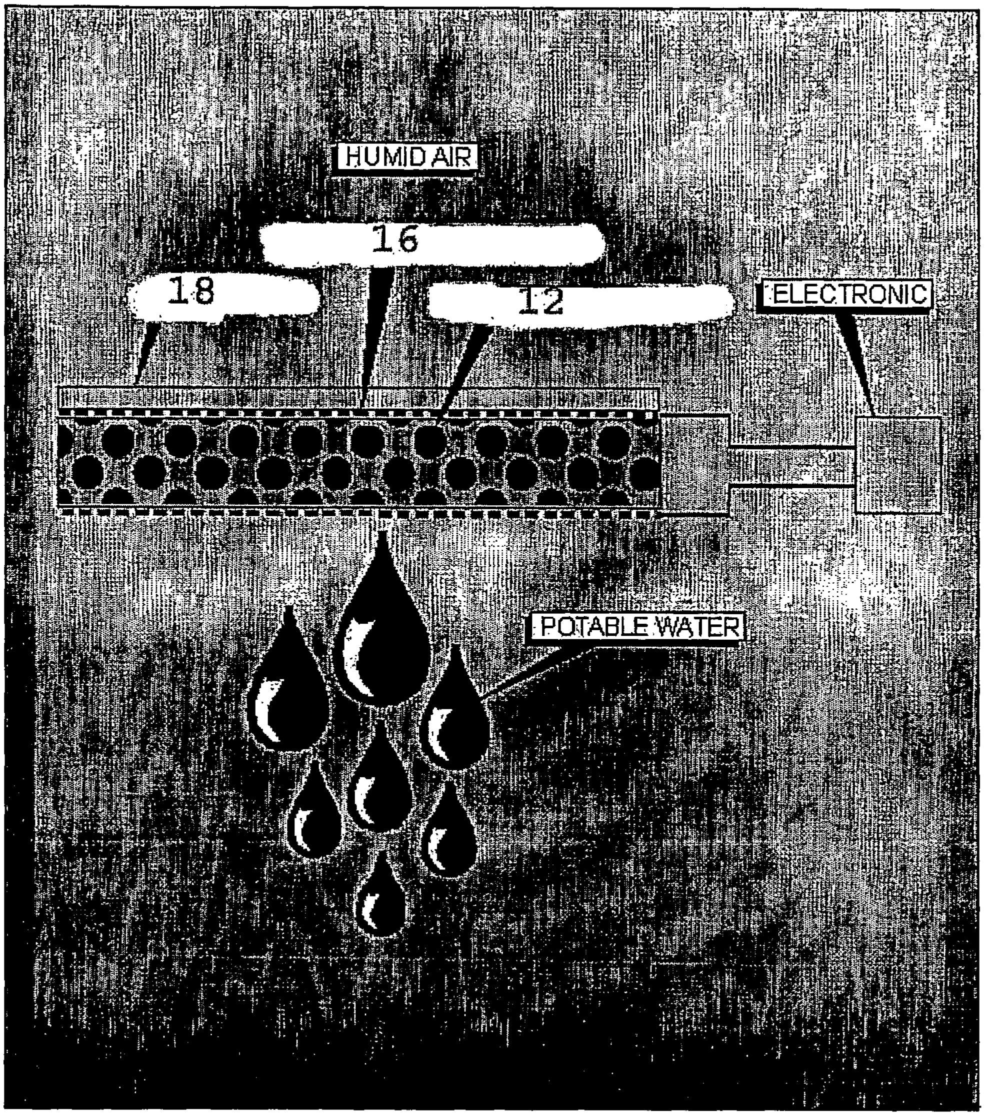


Figure 17

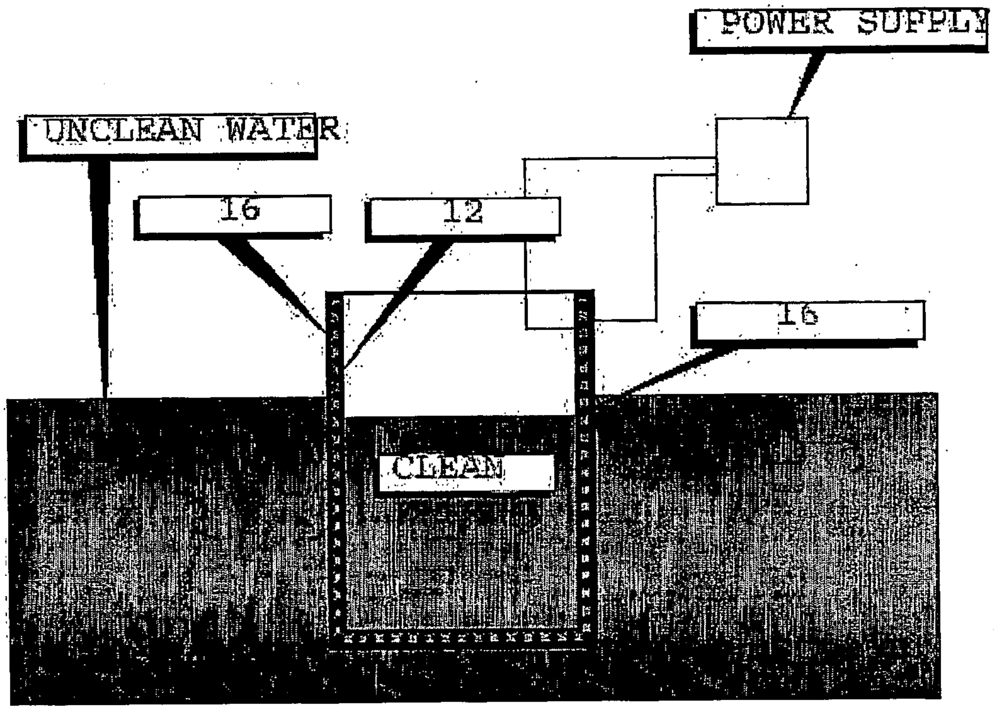


Figure 18